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MECHANISM OF GROUND IMPROVEMENT BY BLASTING TECHNIQUE
발파공법에 의한 지반개량의 작용원리

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개 요(SYNOPSIS):

발파공법은 비 점토성 지반의 심층 개량처리에 있어서 경제적이며 실용성 있는 방법이다. 발파에 의한 흙의 다짐효과는 복잡한 과정을 통하여 이루어지며 좋은 결과를 얻기 위해서는 발파 계획에 있어서 동 공법의 작용원리를 잘 이해하고 적용하여야 한다.

본 연구에서는 발파공법에 의한 흙의 다짐효과에 관한 과거의 연구자료를 광범위하게 조사하였다. 지반개량 작용원리에 관련하여 특별한 현상과 증거를 제시하는 실제 사례 자료를 기초로 하여 현재까지 흙의 밀도증가 요인을 설명해 온 개념은 발파에 수반되어 주변 주반에 발생되는 지반거동현상을 설명하기에 부족함이 있음을 지적하였다. 또한 발파지점 부근에 형성되는 액상화 영역과 그 외부 영역에서 각각 발생되는 과잉간극수압 및 지반응력상태, 이에 따른 지반침하 형태 그리고 개량지반의 강성 및 강도특성에 관하여 고찰하였다.

INTRODUCTION

Needs often arise in practice to improve strength and reduce compressibility of foundation soils for support of many types of structures. When a site is underlain to a great depth by soil deposits unsuitable for support of the structure, both technical and economical reasons dictate the decision to consider deep in-place soil improvement techniques. Among the available techniques, the more commonly used in noncohesive soils include vibroflotation, deep dynamic compaction and blasting.

Blasting was used as early as 1936 in Russia(10) and 1939 in the U.S.A.(19) for deep compaction of dam foundations consisting of sandy soils. Following the first successful application in 1936, numerous projects have utilized blasting in Russia for foundation improvement of sandy to silty soils(10,11). Blast densification practice appears to have virtually ceased in the U.S.A. since the early 1960's, although there were several cases of successful applications during earlier years(24). Since the mid-1960's, blast application has expanded to many other parts of the world for improvement of foundations and slope stability(1,7,8,14,15,24,26,29). In the research front, extensive experimental and theoretical work was done in Russia during the periods of 1950's through 1970'(10), while there was no significant effort in the U.S.A. until the apparent recent revival of interest in the subject(2,5,9,21,22,23,31).

Blasting for ground improvement has been most extensively used in situations involving a vast loaded area and where a considerable amount of uniform settlement is tolerable, such as dams, breakwaters, shoreline dikes and other similar construction. The need for improvement of the foundation soils for these instances is often governed by an inadequate factor of safety against liquefaction due to earthquakes or ocean wave actions and excessive differential settlements. The selection of blasting over other methods is primarily due to its cost effectiveness, practical advantages and the proven technical viability. A recent Canadian experience(7) estimates a cost of $0.33/m3 for blast densification, including test blasts, compared to $2.00 to $3.00 per cubic meter for other methods. Installation of explosive charges can be done with relatively small scale equipment and the soil improvement can be carried to depths much beyond the reach of other methods.

Blast densification is affected by numerous factors, largely because of the complex phenomena involved in the reaction of the soil mass to blasting. Therefore, understanding of the process occurring in the soil mass upon blasting is important for design of a blast densification program. Although blast densification has a long history, not much work has been done on the mechanism of blast densification outside Russia. However, numerous recent cases have produced data and observations pertinent to understanding of the densification mechanism.

Focusing on deep explosions, this paper reviews the previous work done on the blast densification mechanism and explains the mechanism in ways compatible with the evidence and phenomena observed in recent cases. This paper also treats the effect of post-blast aging of sands on strength gain or penetration resistance that has attracted the interest of many in recent years(2, 9, 13, 20, 22, 23, 29).

METHODS OF BLAST APPLICATION FOR GROUND IMPROVEMENT

Blasting is applied in various ways to accomplish the desired soil improvement.

List, et al.(17) has used crater explosions to improve slope stability of sand excavations exposed in mining by disrupting clay seams contained in the sand deposits and lowering the groundwater table behind the slope through the cracks formed by blasting.

Blasting for soil densification commonly uses individual charges, either concentrated at one location or dispersed. In this type of charge placement, the blast is defined "deep explosion", "surface explosion", and "underwater explosion", depending on the location of the charge placement with respect to the ground surface, as shown in Figure 1. In deep explosion, charges are buried deep in the ground and the charge depth and weight are controlled to avoid formation of craters at the ground surface. In surface explosion, the charges are placed immediately below the ground surface. This method is more applicable to treatment of soils to limited depth. Only a fraction of the total energy is consumed for densifying the soil in this case. Underwater explosions require a substantial depth of water, and the charges are suspended in water at an appropriate height above the ground surface to accomplish the best result.

Lateral compaction of soil is achieved by detonating charges linearly distributed in a small vertical hole, as shown in Figure 1-d. This method is termed as "explosion squeezing"[33].

The mechanism treated in this paper focuses primarily on deep explosions, Figure 1-a.

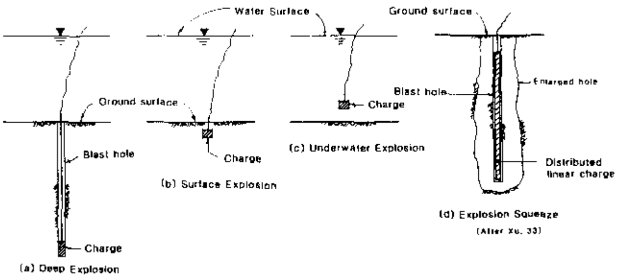


FIG. 1 - METHODS OF BLAST APPLICATION FOR SOIL COMPACTION

BLAST ACTION

Upon detonation, explosives are instantly changed to a gaseous form through chemical reaction, and the resulting volume of the gases may become more than 1000 times the charge volume. When the charges are detonated deep in the ground, the resulting gases produce violent shock waves to the soil mass. The propagation velocity of the shock wave in saturated sandy soils may reach many thousands of meters per second and the peak pressure caused by the passing wave may exceed 140 kg/cm2 (2,000 p.s.i.) near the source[4, 10]. The wave is characterized by a large and abrupt pressure pulse having a steep front near the source and rapidly decays with increasing distance from the source. The duration of the high pulse motion is only several milliseconds. The radial compressive strains and tensile circumferential strains associated with the high pressure pulse create a zone of intensive destruction and irreversible deformation of the soil mass around the source. At greater distances from the source, the shock wave is gradually transformed to seismic waves (a sinusoidal form), with the soil behavior more dominantly effected by shear waves. The pressures resulting from the reaction between the propagating wave and the soil mass generate stresses to the soil particles and excess pore pressure.

The ground surface in the blast area is commonly raised in a mound form during the blast action and then an immediate depression (settlement) of the raised ground surface follows. The depressed ground surface is characterized by a series of semi-parallel concentric cracks. Blowouts of water and gases occur randomly during the period of rapid depression of the ground surface. The ground settlement continues with passage of time, encompassing a gradually widening area.

PREVIOUS WORK ON DENSIFICATION MECHANISMS

The mechanism leading to soil densification by blasting has been extensively treated and formulated by Ivanov[6, 10, 11]. This work, which was originally published in Russian, was introduced in English translation in 1967. Dowding and Hryciwaa[5] and Fordham, et al.[7] have presented a general outline of the mechanism, which essentially followed the concept put forth by Ivanov. No other notable work on this subject appears in the literature outside Russia.

Ivanov, dealing primarily with saturated noncohesive soils, considered that the soil mass must be brought to liquefaction by destruction of the soil structure in order to accomplish an effective compaction, because the main attribute to densification is consolidation of the liquefied soil mass. Therefore, no significant degree of densification should be expected unless the soil structure is completely destroyed by blasting. (He defines the structure of noncohesive soil as "the arrangement of particles of different sizes and forms, their interaction and the nature of bonds between them[10]", and liquefaction as "mechanical breakdown of the soil structure[6]).

He also considered that the volumetric strain caused by the shock wave is a negligible portion of the overall volume change leading to densification. Ivanov regarded that the very action of blast benefiting the soil densification is the pressure generated by the explosion, because it is the pressure that causes mechanical breakdown of the soil structure, which he assumed to be governed by the following equations:

$$\tau + \Delta\tau \le \sigma + \Delta u + \Delta\sigma)\tan\phi \qquad (1)$$

$$p = \Delta\sigma + \Delta u \qquad (2)$$

here: and σ: shearing and normal stresses acting on soil skeleton before blasting
p: pressure generated by shock wave
$\Delta\sigma$ and Δu: skeleton stress and excess pore pressure generated by p, and
ϕ: angle of internal friction.

Based on Eq. 1, Ivanov suggested a method called "layer-by-layer destruction of structure". In this method, charges are placed at several separate locations vertically in the same hole, and detonated with milliseconds delays, starting from the uppermost one. He considered that the sequential liquefaction of the layers commencing from the uppermost layer would reduce or eliminate the effective overburden pressure acting on the soil particles in the subsequent layer for blasting, thus the liquefaction process or destruction of the soil structure for the entire depth of soil densification zone would be facilitated. On this basis, he also suggested that the delays between the successive explosions in the same hole should be determined so as to allow for least dissipation of the excess pore pressure generated by the previous explosion.

REVIEW OF PREVIOUS CASES

The layer-by-layer structure destruction concept introduced by Ivanov was employed in a blast test program for a harbor construction at Zeebrugge on the Belgian coast[1]; however, the results did not conclusively support the concept. The foundation improvement at Jebba dam in Nigeria[29] was successfully done by blasting a concentrated charge placed at a depth of 45 meters below the surface and the concept of layer-by-layer structure destruction was not followed. Dowding and Hryciw[5] performed a laboratory experiment aimed at evaluating the advantage of millisecond delays between successive detonations. In their study, two tests, each detonated two charges simultaneously (zero millisecond delay), produced a post-blast relative density of 74% and 78%, while four tests, each detonated two charges with milliseconds delays ranging from 17 milliseconds to 50 milliseconds, produced a post-blast relative density in the range of 74% and 76%, indicating no apparent advantage of the layer-by-layer structure destruction concept.

In experiences with application of "explosion squeezing", Xu[33] reports that a small hole (presumably several cm in diameter) drilled into a loess deposit was enlarged to 45 cm in diameter and dry density of the deposit was increased by an average of 15% when the blast holes were located with a spacing of 135 cm. Kummeneje and Eide[15] report of results of screw-plate loading tests performed to confirm the effectiveness of blasting for improving a thick coastal deposit of silty sand. From the results of their test program, they identified a highly disturbed and loosened spherical zone having an approximate diameter of 5 meters around the blast point. Hryciw and Dowding[9] present data confirming a loosened zone, similar in extent to the one described by Kummeneje and Eide. The Jebba dam site experience[22, 23, 29] also indicated the presence of zones in which the post-blast cone penetration resistance was significantly lower than the pre-blast values immediately after blasting. In the Jebba dam case, the overburden pressure was extremely high (over 40 meters of sand depth). In a crater blasting conducted by List, et al.(17) in oilsands interbedded by thin layers of clay, two zones of ground disturbance were identified on the free surface or the ground surface: a zone of complete isolation of material extending a scaled distance of two times the scaled depth of the charge and a zone of block failures due to rebound extending a scaled distance equal to four times the scaled depth. Scaled depth and scaled distance are defined as follows:

$$D_s = D\,(C^{-1/3}) \qquad (3)$$

$$R_s = R\,(C^{-1/3}) \qquad (3)'$$

where: D_s and R_s : scaled depth and scaled distance
D and R : actual depth and distance, and
C : weight of explosive charge.

Sand deposits also can be compacted by other methods. De Wolfe, et al.(3) report of compaction of dumped sand using a vertically vibrating probe lowered into the sand layer below deep water. The probe effectively compacted the sand over an area up to 12 m2. Youd(32) suggests that repeated shear straining can cause compaction in sandy soils. Lukas(19) reports of a successful compaction of loose deposits by pounding, a method similar to dynamic deep compaction. Also, earthquakes induce settlement to loose sand deposits, and the volume change behavior of sands under cyclic loading conditions has been extensively studied(28).

The evidence and phenomena observed in the blast cases discussed above suggest that:

1. The general validity of the concept of "layer-by-layer destruction of structure" is not well supported.

2. Volumetric strains developing in the soil mass during the blast action appear to be a significant portion of the overall volume change leading to densification of the soil.

3. The blast action inevitably creates a large zone of intensive destruction and irreversible deformation of the soil mass around the blast point even under very high overburden pressure.

4. Densification of soil deposits by the various loading methods discussed above, excluding blasting, is accomplished without the destruction of soil structure leading to complete liquefaction to the extent experienced in blasting. Therefore, it may be concluded that complete breakdown of soil structure is not necessarily the condition wholly governing the effectiveness of compaction by blasting.

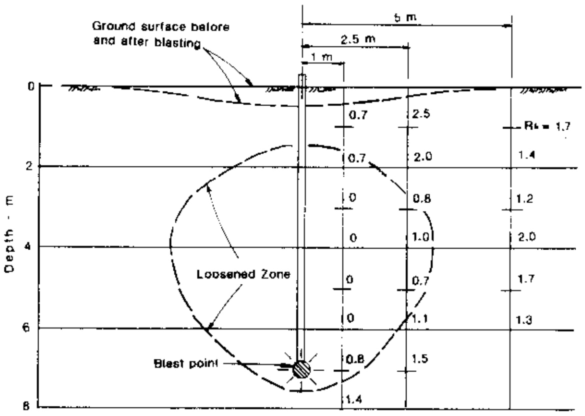
REALISTIC MECHANISMS OF BLAST DENSIFICATION

It is now well established, as discussed previously in the review of several blast cases, that a large zone of loosened or intensive destruction of the soil mass is formed around the blast point, and the ground settlement extends far beyond the limit of the loosened zone. Therefore, it should be considered that the densification within and outside the loosened zone is controlled by characteristically different mechanisms.

Liquefaction Zone

Both the extent of the loosened zone and the densification mechanism within the loosened zone are important considerations in blast design analysis. Upon blasting, a cavity will be formed at the blast point by an elastic mechanism, in a similar way as in the case of "explosion squeezing" reported by Xu(33), and it could be considered that the expansion of the loosened zone is caused by a fluidization mechanism, such as dynamic fluidization and hydraulic fluidization (flotation). Statically stable soil mass can enter a state of flotation under dynamic excitation(25). Hydraulically induced fluidization is also a well understood phenomenon(16). The soil mass involved in the flotation would completely liquefy, and the cavity space will then be filled by the liquefied material. The liquefaction zone may be compared to the zone of complete material separation reported by List, et al.(17) in a crater explosion. Obviously, the process forming and expanding the loosened zone is highly complex and practically difficult to investigate precisely because instrumented studies are not possible near the blast point.

Several notable contributions have been made concerning the extent of the loosened zone, or liquefied zone(9, 10, 14, 15, 30). The presence and extent of the loosened zone was most clearly presented by Kummeneje and Eide(15) in their early work (1961) in which they compared the screw-plate loading resistance before and after blasting at various distances away from the blast points, as shown in Figure 2.



Rs: Settlement ratio of screw-plate under 3 kg/sq. cm before and after blast of 6.9 kg charge

(After Kummeneje and Eide, 15)

FIG. 2 - SCREW-PLATE LOADING TEST RESULTS

Studer and Kok(30) established an empirical equation defining the generation of excess pore pressure in a buried single charge explosion, and it was given by:

$$\frac{\Delta u}{\sigma_o} = 1.65 + 0.64 \ln \frac{C^{0.33}}{R} \qquad (4)$$

where C : charge weight, kg
R : distance from blast point, m
Δu : excess pore pressure, and
σ_o : effective octahedral stress.

It is often more convenient to express the excess pore pressure ratio of Eq. 4 in terms of the effective vertical pressure. For deposits in coastal settings or not significantly overconsolidated, Eq. 4 may be expressed in terms of the effective vertical pressure by using a value of 0.5 for the in-place earth pressure coefficient. Then, Eq. 4 may be rewritten as:

$$\frac{\Delta u}{\sigma'_v} = 1.10 + 0.43 \ln \frac{C^{0.33}}{R} \qquad (5)$$

where, σ'_v: effective vertical pressure.

Excess pore pressure ratios calculated from the above equation are compared below with the data obtained by Kummeneje and Eide from a detonation of a 1.2 kg charge at a depth of 7 m in sandy to silty soil:

Distance, R, m :	5	10	20
Eq. 5:	0.43	0.14	0
Kummeneje & Eide:	0.42	0.11	0.04

When the excess pore pressure ratios approach either unity as calculated by Eq. 4 or to 2/3 as calculated by Eq. 5, liquefaction would occur and a blowout could happen when the ratios significantly exceed these limits in the respective cases. Therefore, these equations may also be used as a general guide in determining the charge weight and depth to avoid formation of craters at the ground surface in the blast design analysis.

Maximum ground settlement is commonly experienced directly above the blast point, as shown in Figure 3, which is based on the data obtained by Kummeneje and Eide(15). The settlement profiles shown in Figure 3 were obtained by successive blasts in the same hole and at the same depth, with time allowed between the blasts for a full dissipation of the excess pore pressure. Several interesting points may be observed in Fig. 2 and 3. These include:

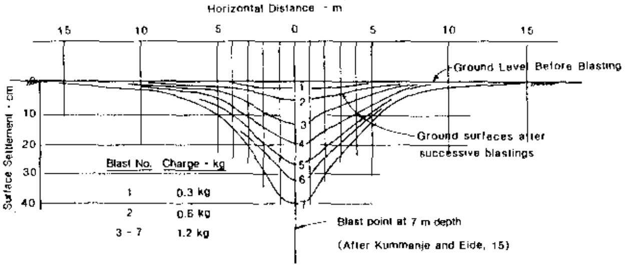


FIG. 3 - SURFACE SETTLEMENT AFTER SUCCESSIVE BLASTS

a) The convexity of all profiles begin to develop at a horizontal distance close to 2.5 meters from the blast point, and this distance roughly coincides with the lateral extent of the loosened zone shown in Figure 2.

b) The ground settlement beyond the beginning of convexity in the profile is not significantly increased with increase in the number of repetitions in blasting, whereas the settlement within the concave portion (or loosened zone) accumulates at a large magnitude in each blast.

c) The loosened zone expands mostly upward and laterally from the blast source, and does not extend deep below the blast point. (other cases indicate the loosened zone to extend greater depths(9, 14) than this case below the blast point.)

The above observations are generally typical for deep explosions. No data or records are available that directly explain whether or not the large increase of the ground settlement between the blasts within the concave portion of the profile leads to a corresponding increase in the degree of compaction in that zone. However, there are certain findings available from the past experiences that can be linked to the mechanism developing in the liquefied zone. These include:

i) When charges of same weights are successively detonated, with the excess pore pressure allowed to dissipate fully between blasts, the ground settlement from each blast becomes less than the one preceeding.

ii) Both the dilatometer test (DMT) modulus and horizontal stress index decreased after blasting(9).

iii) Cone penetration test (CPT) tip resistance (q_c) was reduced after blasting(7, 9, 22), even when no excess pore pressure was present, and the radial extent of decreases in qc agreed well with the extent of liquifaction zone determined by Eq. 4(9).

iv) qc increased with time(2, 13, 20, 22, 23).

v) Decrease in qc was much less in vibrocompaction than in blasting(22).

The ground settlement profiles noted in Item (i) above may represent the total reduction of the soil volume that leads to densification. However, distribution of compaction along the profile is not known. Therefore, the settlement profile alone is not sufficient to conclude that the settlement is proportional to compaction at each location. It is more probable that the increases in settlement following the successive blasts are due to expansion of the liquefied zone that was discussed earlier, rather than representing increased densification. Densification of this zone then would be attained through a consolidation process.

The mechanism defined above presents important practical implications concerning blast densification designs. These include the following:

a) The loosened zone, or completely liquefied zone, is an inevitable product of blasting. Since densification of this zone is attained through a consolidation process, the charge depth is an important parameter to consider.

b) Enlargement of the liquified zone is not a benefit to the densification process. Therefore, delays between the successive blasts should be long enough to allow for a full dissipation of the excess pore pressure generated by the previous blast.

c) Placing surcharge fills at the blast location before detonation would benefit the densification process, because the increased overburden pressure will direct more energy to the radial direction and induce greater densification in the liquefied zone. This consideration is justified only when the mechanism defined above is accepted, and is contrary to the concept of layer-by-layer destruction of soil structure.

Outside the Liquefaction Zone

It was mentioned earlier that the soil mass bounding the liquefied zone would be subjected to an elastic compression during the blast action. The zone which undergoes the elastic compression is similar to the zone of fragmentation (or block failures) due to rebound that was identified in the crater blasting described by List, et al.(17). The fragmentation zone was found to be twice the extent of the complete material separation zone. Therefore, the extent of the elastic compression zone could be approximated to be twice the extent of liquefaction zone determined by Eq. 4 or 5. In addition to the elastic compression, this zone would also experience relative displacements of the particles and generation of excess pore pressure by the shock waves. It would be reasonable to consider that this zone receives the greatest compaction during the blast action.

The extent of the area beyond the compression zone described above may be called the balance zone. The soil behavior in this zone would be governed by the more orderly developing seismic waves. The repeated shear straining mechanism described by Youd(32) and the seismically induced mechanism as described by Silver and Seed(28) would be the major factors causing densification of this zone. This zone may extend a great distance. However, the extent of this zone meaningful for practical purposes is the limit where an acceptable level of compaction is attained. Ivanov(10) suggested an empirical equation defining the distance to 1 cm ground settlement boundary in the following form:

$$Rc = k\,C^{0.33} \qquad (6)$$

where, Rc : distance to 1 cm ground settlement line, m,
C : charge weight, kg, and
k : empirical coefficient (Table 1).

TABLE 1 - k Values

Soil Gradation	Relative Density	k
Fine sand	0 to 20%	25 - 15
" "	30 to 40%	9 - 8
" "	over 40%	less than 7
Medium sand	30 to 40%	8 - 7
" "	over 40%	less than 2.5

Effect of Post-Blast Aging of Sands on Strength

The phenomenon of strength gain with the post-blast aging in sands observed in connection with the experience at the Jebba dam project in Nigeria(22, 23, 29) has attracted much attention in recent years. This phenomenon was first detected by increases in the cone penetration test resistance in the blasted area with the passage of time. The importance of recognizing and understanding this phenomenon in the ground improvement technology may include the following:

a) Deep ground improvement techniques rely upon the results of in-situ tests for verification of the results. Usually the standard penetration test (SPT) or the cone penetration test (CPT) is used for such purpose. The penetration resistances obtained before and after blasting are compared for this purpose. Therefore, unless this phenomenon is recognized and properly accounted for, erroneous verifcations could result.

b) Timing for imposition of loads on the improved area and the stability analysis should consider this phenomenon.

Various hypotheses have been presented to explain this phenomenon. Mitchell and Solymar(22) consider the dissolution and precipitation of silica causing cementation at the particle contacts could be the major factors, and indicate that the reactions may continue for periods up to a few years. Schmertmann(27) considers that blasting would temporarily decrease effective lateral stresses and the increase in CPT resistance with time could be related to recovery of the effective lateral stresses with time. Hryciw and Dowding(9) confirmed in a blasting experiment that lateral stresses decrease as a result of blast action. Charlie, et al.(2) indicate that the ground temperature affects the rate of increase with time in the tip resistance in CPT. Mesri, et al.(20) cite the continued rearrangement of sand particles during secondary compression as the factor causing the aging effect. Kaniraj, et al.(13) report, through an experimental study, that the aging effect is more pronounced in sea water than fresh water, and in submerged, saturated sands than partially saturated sands.

The Jebba dam experience indicates that the decrease in q_c was much greater, and also the increase in q_c with time, in blasting than vibrocompaction. Since rearrangement of the sand particles would be more extensive in a more disturbed zone, the aging effect would be more important for the liquefied zone.

SUMMARY AND CONCLUSIONS

Blasting is an attractive method for deep ground improvement because of its cost, practical advantages and technical viability.

There is extensive evidence indicating that the effectiveness of compaction by blasting in noncohesive soils is not necessarily determined by the destruction of soil structure causing a state of complete liquefaction. Ivanov's concept that the destruction of the soil structure must occur if densification is to be effectively achieved has a shortcoming in adequately explaining the complex nature of the mechanisms involved in the blast densification process.

The phenomena observed in actual cases and the extensive evidence available suggest that the process involves several zones which are controlled by characteristically different mechanisms. These zones include:

a) Liquefaction zone,
b) Elastic compression zone, and
c) The balance zone.

It is considered that the liquefaction zone is formed and expanded by the combination of the elastic compression of the soil mass surrounding the blast point and the dynamic and hydraulic flotations. Characteristics of the liquifaction zone include significant decreases in qc compared to the pre-blast level and large increases in qc with aging: densification by a consolidation process: and a possible rearrangement of sand particles during secondary compression. The extent of the liquefaction zone may be determined by Eq. 4 or 5.

The elastic compression zone is considered to be controlled primarily by the radial compression and tangential tension and secondarily by relative displacements of particles associated with the passage of the shock wave and consolidation. This zone will receive the greatest compaction during the blast action. The extent of this zone is approximately twice the extent of the liquefaction zone.

The balance zone will be more dominantly controlled by the seismic waves, and thus the relative particle displacements and consolidation due to dissipation of excess pore pressures set up by the waves would be the mechanism causing densification. The extent of this zone may be determined by Eq. 6 for all practical purposes.

Based on the mechanism described for the liquefaction zone, surcharge fills placed over the liquefaction zone can significantly increase the effectiveness of blast densifcation.
However, the surcharge fill application is not justified when the concept of layer-by-layer destruction of structure is followed.

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